Chapter Outline

Hardware Selection Metrics and Communication Mechanisms

Chapter 9 Multi-Vehicle Communication and Intelligent Networking

9.1 Networking Fundamentals

9.2 Hardware and Link Mechanisms

9.3 Software Layers and Protocols

9.4 Channel and Interference Modeling

9.5 RflySim Networking and Simulation

9.6 Protocols and Development Interfaces

9.7 Experiments and Validation

9.8 Exercises and Classroom Discussion

4 Units in This Section

9.2.1 Communication Performance Parameters

Textbook: Section 9.1.3.1

9.2.2 Communication Mechanisms and Anti-Jamming

Textbook: Section 9.1.3.2

9.2.3 Hardware Characteristics and Interface Connections

Textbook: Section 9.1.3.3

9.2.4 Task-Based Hardware Selection Example

Textbook: Section 9.1.3 (integrated application)

9.2.1 Communication Performance Parameters: Task and Selection Criteria

Requirements for Four Nodes Exchanging State

Task data	→	Link metrics	→	Onboard integration
State / video		Rate / latency		Power / interfaces

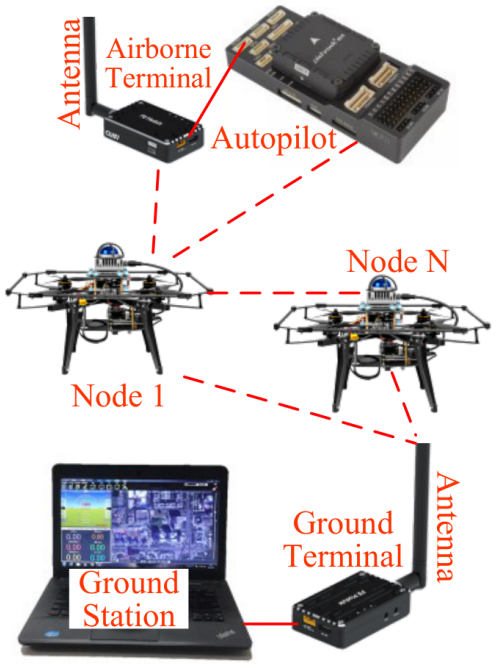
Teaching assumptions: 4 nodes exchange state. Each generates 50 messages/s with 100 B of payload per message.

Selection constraints: Range, usable capacity, packet loss, latency, weight, and power requirements must all be met.

Link options: Wi-Fi, cellular, Long Range (LoRa), satellite, millimeter-wave, and dedicated data links. Mesh describes a network topology.

9.2.1 Communication Performance Parameters: Overview of Figure 9.2

Typical Data Link Product Parameters



Frequency Range: 840-845 MHz
Radio Modes and Modulation: Frequency Hopping / Fixed Frequency, Transparent Transmission, GMSK, 2GFSK, 4GFSK, QPSK
Error Control: 32-bit CRC, ARQ
Communication Range: Reference Distance: 40 km (Air-to-Ground, Suburban Unobstructed; Actual Range Varies by Environment)
Transmit Power: 100 mW ~ 1000 mW (20 ~ 30 dBm); Default: 1000 mW
Link Rate: Up to 345 kbps
Operating Modes: Point-to-Point, Relay Mode
Input Voltage: 12-60 V
Current Consumption: Sleep: < 1 mA; Idle: 20 mA; RX: 45 mA ~ 98 mA; TX (Peak): 2 A
Operating Temperature: -40℃ ~ 85℃
Dimensions: 64.6 mm × 39.7 mm × 16.5 mm
Weight: 55 g (w/o Antenna); Antenna: 31 g; Total: 86 g
Interfaces: Serial (GHR-06V-S); USB (Type-C); Antenna (SMA Male)

Figure 9.2 Typical data link product parameters

CRC (cyclic redundancy check) detects errors; ARQ (automatic repeat request) retransmits.

9.2.1 Communication Performance Parameters: Communication Details in Figure 9.2

Communication Specifications Need Test Conditions

Frequency Range: 840-845 MHz
Radio Modes and Modulation: Frequency Hopping / Fixed Frequency, Transparent Transmission, GMSK, 2GFSK, 4GFSK, QPSK
Error Control: 32-bit CRC, ARQ
Communication Range: Reference Distance: 40 km (Air-to-Ground, Suburban Unobstructed; Actual Range Varies by Environment)
Transmit Power: 100 mW ~ 1000 mW (20 ~ 30 dBm); Default: 1000 mW
Link Rate: Up to 345 kbps
Operating Modes: Point-to-Point, Relay Mode

Figure 9.2 (detail) Communication parameters

CRC detects errors; ARQ retries. Verify rate and range maxima against their test conditions.

9.2.1 Communication Performance Parameters: Frequency Bands

Frequency and Communication Technology Are Separate Dimensions

Name	Frequency meaning	Common task uses
VHF: Very high frequency **UHF: Ultra high frequency**	VHF: 30–300 MHz UHF: 300 MHz–3 GHz	Private, relay, and air−ground links. Band alone cannot guarantee immunity.
433 / 915 MHz	Specific bands below 1 GHz	Low-volume telemetry. Licensing, power, and uses vary by region.
2.4 / 5 GHz	Common wireless local area network bands	Short-range state and video. Shared spectrum creates contention.
5.8 GHz	A group of frequencies near 5 GHz	Common for video. Line of sight and antennas affect coverage.

ISM: industrial, scientific, and medical. License exemptions differ by region.

9.2.1 Communication Performance Parameters: Wi-Fi, LoRa, and Cellular

Different Terrestrial Wireless Technologies Serve Different Needs

Technology	Main uses	Selection conditions
Wi-Fi / NearLink	Local high-rate links. SLE: SparkLink Low Energy. SLB: SparkLink Basic.	Band, access mode, capability, and shared-channel contention
LoRa	Low-power, low-volume telemetry using chirp spread spectrum (CSS)	Better reception costs airtime. Rate: chip and settings.
4G LTE / 5G NR	Wide-area access, video, cloud sync. LTE: Long-Term Evolution; NR: New Radio.	Coverage, cost, uplink, and load. Assess coverage at altitude.
5G-Advanced (5G-A)	Further evolution of 5G capabilities	Capabilities depend on terminals, networks, and configuration.

Textbook “LoRa < 50 kbit/s” illustrates low-rate use, not a universal device limit.

9.2.1 Communication Performance Parameters: Satellite Bands and Conditions

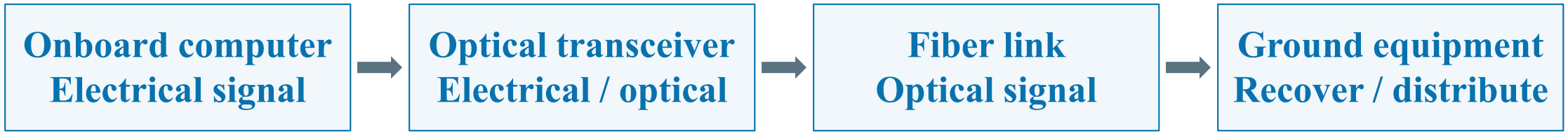
Satellite Links Extend Network Reach

Band / system	Textbook context	Operating conditions
L: 1–2 GHz	Mobile terminals, telemetry, and position reporting	Service rate and device power consumption depend on the system.
Ku: 12–18 GHz **Ka: 26–40 GHz**	Common bands for broadband satellite links	Check service frequencies. Rain fade, blockage, and pointing affect the link.
Low-Earth-orbit broadband constellations	Examples: Starlink, GW (Guowang), and Qianfan	Satellites, ground gateways, and user terminals work together.

Textbook example from 2025: Starlink had over 7,600 satellites and 20–50 ms latency.
Date, region, and counting or latency metrics vary. These are not selection guarantees.

9.2.1 Communication Performance Parameters: Special Wired Links

Fiber Links Introduce Different Deployment Constraints



Benefits: High-volume data return. The fiber medium is immune to radio-frequency (RF) interference, and ground computing can be centralized.

Limits: Cable weight, deployed length, bending, and snagging constrain movement. A broken fiber interrupts the link.

Textbook scenarios: 4K/8K video and cable runs from hundreds of meters to tens of kilometers refer to specific configurations, not general capabilities.

9.2.1 Communication Performance Parameters: Transmit Power

Converting Transmit Power Units

$$P_{\mathrm{dBm}} = 10 \log_{10} \left(\frac{P}{1\ \mathrm{mW}} \right)$$

RF output power	Equivalent value	Ratio
100 mW	20 dBm	Reference for this comparison
500 mW	About 27 dBm	5 times 100 mW
1 W = 1000 mW	30 dBm	10 times 100 mW

dBm references 1 mW. P is RF output power; P_{dBm} is its dBm value.
Higher power adds supply and cooling demands; range does not rise proportionally.

9.2.1 Communication Performance Parameters: Bandwidth, Rate, and Throughput

Spectrum Bandwidth and Data Rate Use Different Units

Metric	Definition / units	Textbook example / meaning
Spectrum bandwidth	Occupied or allocatable spectrum Hz, MHz	20 / 40 MHz describes frequency resources.
Data rate	Bits transmitted per unit time bit/s, Mbit/s	For example, 150 Mbit/s. Specify the protocol layer.
Payload throughput	Application payload delivered / time bit/s	Below nominal rate in most cases. Losses and overhead use capacity.

Video and point clouds need capacity; state and commands also need timely delivery.

9.2.1 Communication Performance Parameters: Range and Link Margin

The Entire Link Determines Maximum Range

Transmitter Power / coding	→	Antennas / environment Gain / loss	→	Receiver Sensitivity / decoding

Internal factors: Antenna directivity, feeder loss, frequency, modulation and coding, and receiver sensitivity act together.

External factors: Buildings, terrain, vegetation, multipath, co-channel interference, and weather change usable range.

Link margin: 5 / 10 / 30 km are example operating conditions. Received signal margin above the decoding threshold accommodates variation.

9.2.1 Communication Performance Parameters: Link Reliability

Bit Errors and Packet Loss Measure Different Events

$$\mathrm{BER} = \frac{N_{\text{error bits}}}{N_{\text{observed bits}}} = \frac{10}{10^6} = 10^{-5}$$

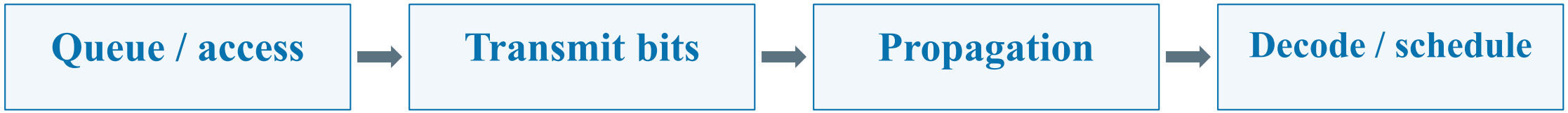
$$\mathrm{PLR} = \frac{N_{\text{missing packets}}}{N_{\text{sent packets}}} = \frac{20}{1000} = 2\%$$

Bit error rate (BER): erroneous bits / observed bits.
Packet loss rate (PLR): missing packets / sent packets.
N counts items. Both are assumed; keep each window and packet sequence consistent.

Engineering meaning: Retransmission can recover some losses, but consumes capacity and adds waiting. Stale state may still be useless.

9.2.1 Communication Performance Parameters: Sources of Latency

Components of End-to-End Latency



$$t_{\text{prop}} = d/c = 100000/(3 \times 10^8) \approx 0.33\,\text{ms}$$

$$t_{\text{tx}} = 8L/R = 8 \times 1000/10^6 = 8\,\text{ms}$$

Propagation delay t_{prop} and transmission delay t_{tx} are both expressed in ms.
d: path length (m). c: speed of light (m/s). L: packet length (B). R: link rate (bit/s).
Example: 100 km, 1000 B, and 1 Mbit/s. Access, processing, and retransmission are excluded.

Buffers, scheduling, protocol processing, and retries add delay. The task sets the limit.

9.2.1 Communication Performance Parameters: Timestamps and Apparent Delay

Clock Offset Distorts One-Way Delay Measurements

Event / condition	Sender's time base	Receiver's record
Transmission	100 ms	Receiver clock is 30 ms ahead.
Arrival 10 ms later	110 ms	140 ms
Subtract local timestamps	Actual elapsed time: 10 ms	Apparent delay: 40 ms

Assume a fixed 30 ms clock offset. One-way delay needs a shared time base.
GNSS: global navigation satellite system. PTP: Precision Time Protocol. Both can synchronize clocks.

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Textbook: Section 9.1.3 (integrated application)

9.2.2 Communication Mechanisms and Anti-Jamming: Point-to-Point, Star, Relay, and Multihop

Networking Mode Changes the Forwarding Load

Mode	Data path	Main tradeoff
Point-to-point	A directly to B	Simple path. Coverage is limited to one link.
Star	A through the center to B	Central management, with central-node load and a single point of failure
Relay	A through B to C	Extends coverage, with an extra forwarding operation
Multihop ad hoc network	Nodes discover neighbors and maintain paths.	Adapts to topology changes, with routing maintenance overhead

A star is a network. Multihop adds path selection and access/forwarding load at each hop.

9.2.2 Communication Mechanisms and Anti-Jamming: QPSK, 16QAM, and GMSK

Modulation Trades Data Rate Against Symbol Separation

Scheme	Signal representation	Benefit / cost
QPSK **Quadrature phase-shift keying**	4 phases, 2 bits per symbol	Wider spacing; fewer bits at a given symbol rate.
16QAM **16-level quadrature amplitude modulation**	16 amplitude / phase states 4 bits per symbol	More bits at equal symbol rate; requires a better signal-to-noise ratio.
GMSK **Gaussian minimum shift keying**	Gaussian-filtered continuous-phase modulation Constant envelope	Compact spectrum and efficient power amplification. Rate varies by configuration.

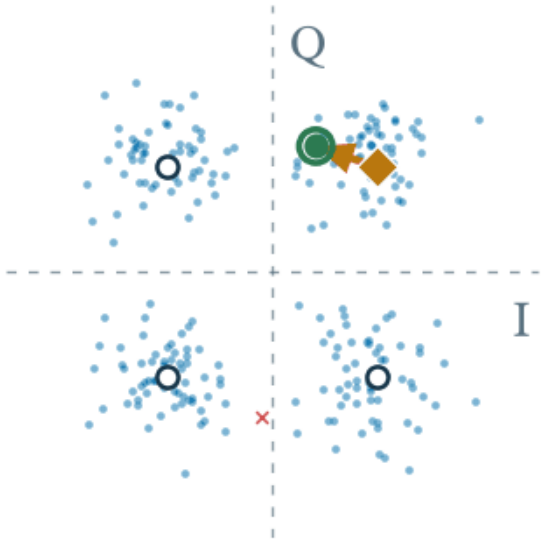
A symbol is one distinguishable signal state. LoRa uses CSS, rather than GMSK.

9.2.2 Communication Mechanisms and Anti-Jamming: Constellations and Decisions

Noise Can Push a Received Symbol Across a Decision Boundary

Equal mean symbol energy $E_s = 1$ — Same AWGN samples $\sigma_{I,Q} = 0.24$

QPSK · 2 bit/symbol



Sent → decided

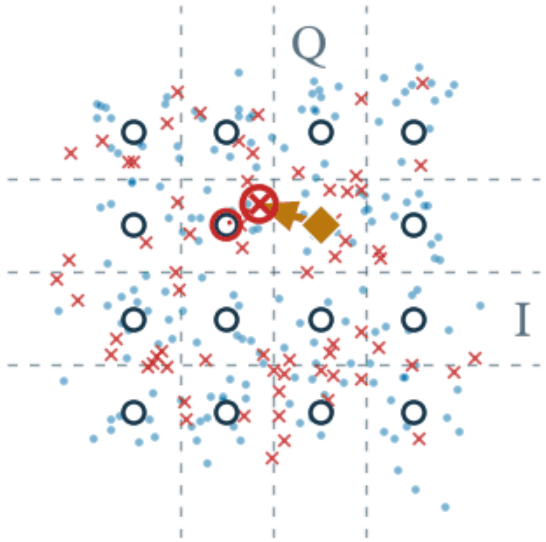
11 → 11

◆ Correct symbol

$d_{min} = 1.414$

Errors 1/256

16QAM · 4 bit/symbol



Sent → decided

1111 → 0111

◆ 1 bit error

$d_{min} = 0.632$

Errors 68/256

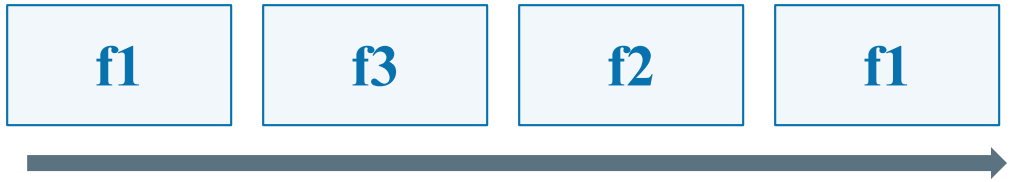
Uncoded ○ Ideal • Received × Error ----- Decision boundary

I/Q: in-phase/quadrature. AWGN: additive white Gaussian noise. $d_{\min}$: minimum spacing.

9.2.2 Communication Mechanisms and Anti-Jamming: FHSS and DSSS

Frequency Hopping and Direct Sequence Spreading

Frequency hopping spread spectrum (FHSS): switches frequencies over time



Time advances; both ends follow one sequence.

Direct sequence spread spectrum (DSSS): maps bits to chip sequences



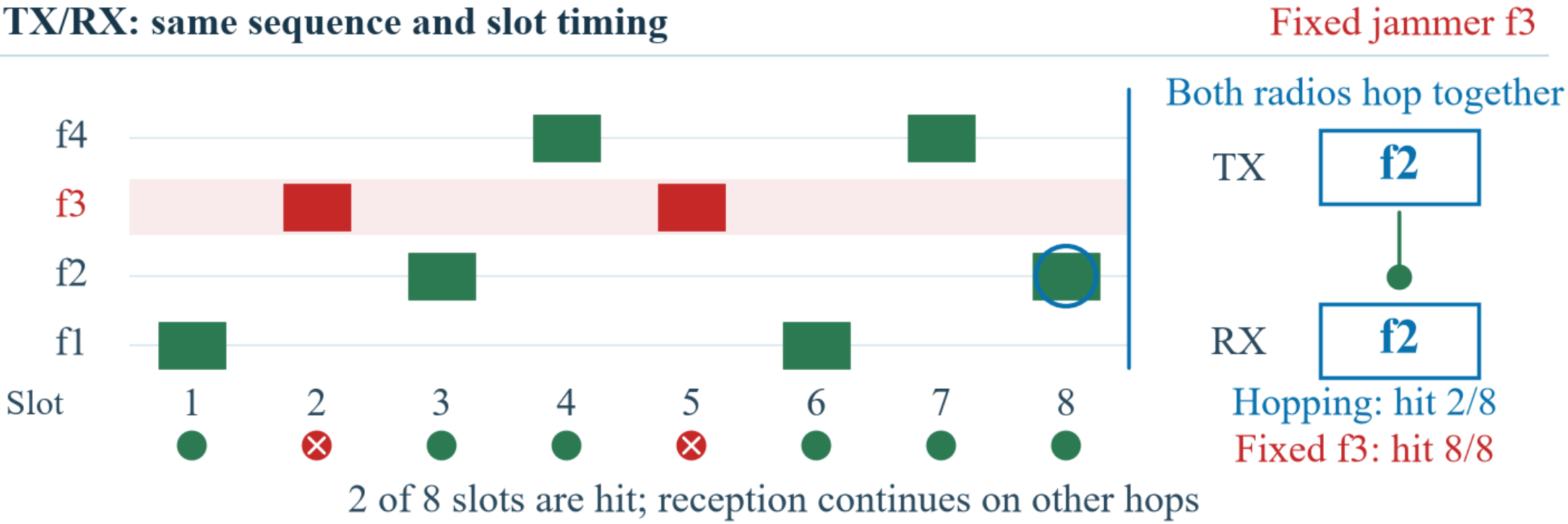
Correlation despreads and recovers data. A chip is a basic spreading-code unit.

Interference mitigation: Hopping limits narrowband interference to some frequencies. Direct sequence spreading uses correlation to suppress uncorrelated interference.

Shared costs: Synchronization, spectrum, or airtime overhead. Effectiveness depends on interference bandwidth, strength, and channel conditions.

9.2.2 Communication Mechanisms and Anti-Jamming: Hopping Synchronization

Synchronized Hopping Limits Narrowband Interference Exposure

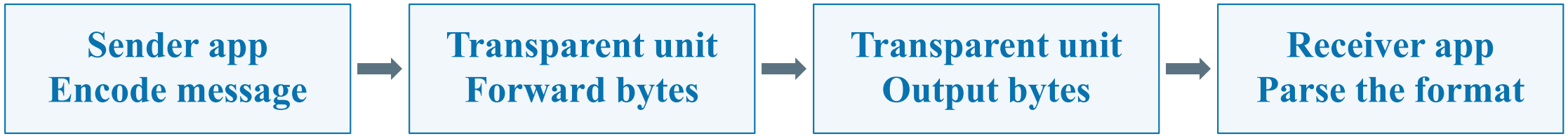


Synchronized hopping: time-slot overlap with fixed narrowband interference

Synchronize sequence and slots. Narrowband interference still corrupts overlapping slots.

9.2.2 Communication Mechanisms and Anti-Jamming: Transparent Transport

Transparent Transport Forwards Bytes



Shared meaning: Both ends need matching field order, units, frame boundaries, and versions to interpret the data correctly.

Upper-layer formats: Micro Air Vehicle Link (MAVLink) messages; National Marine Electronics Association (NMEA) navigation sentences; Modbus industrial communication.

Device behavior: Transparency concerns upper-layer meaning. Lower layers may buffer, detect errors with CRC, and retransmit with ARQ.

9.2.2 Communication Mechanisms and Anti-Jamming: Parity, CRC, FEC, and ARQ

Error Detection, Correction, and Retransmission

Mechanism	Action	Cost / limit
Parity / CRC	Parity bits / CRC detect errors.	May miss errors. No correction or retry.
Forward error correction (FEC)	Redundant coding corrects some errors. Reed-Solomon / convolutional codes.	Capacity / computing cost. Limited correction.
Automatic repeat request (ARQ)	ACK: acknowledgment of receipt. NACK: negative acknowledgment. Retry on NACK or ACK timeout.	Feedback, capacity, and latency costs.
Hybrid ARQ (HARQ)	Combines error-correction coding with retransmission.	Redundancy, retries, and timeliness trade off.

9.2.2 Communication Mechanisms and Anti-Jamming: Reliability and Timeliness Example

A Successful Retransmission Can Miss the Deadline

Time (assumed)	Link event	Application decision
0 ms	Generate and send state.	Set a 25 ms deadline.
10 ms	Initial transmission fails.	No usable state yet.
20 ms	Timeout and retransmission	Waiting consumes the time budget.
30 ms	Retransmission succeeds.	Correct but stale: beyond the 25 ms deadline.

All times are assumed. Error recovery helps only while the recovered data remains usable.

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Textbook: Section 9.1.3.3

9.2.4 Task-Based Hardware Selection Example

Textbook: Section 9.1.3 (integrated application)

9.2.3 Hardware Characteristics and Interface Connections: Hardware Details in Figure 9.2

Power and Interfaces Belong in the Specification Check

Input Voltage: 12-60 V
Current Consumption: Sleep: < 1 mA; Idle: 20 mA; RX: 45 mA ~ 98 mA; TX (Peak): 2 A
Operating Temperature: -40℃ ~ 85℃
Dimensions: 64.6 mm × 39.7 mm × 16.5 mm
Weight: 55 g (w/o Antenna); Antenna: 31 g; Total: 86 g
Interfaces: Serial (GHR-06V-S); USB (Type-C); Antenna (SMA Male)

Figure 9.2 (detail) Hardware and interface parameters

Peak current sets transient supply needs; weigh antennas, cables, adapters, and mounts too.

9.2.3 Hardware Characteristics and Interface Connections: Integration and Power Example

Size, Weight, and Power Jointly Constrain Integration

Another textbook example (not Figure 9.2)	Integration implications
80 mm × 60 mm × 20 mm, 90 g	Allow space for mounting, cooling, antennas, and cables.
Operating voltage: 5–12 V. Power: about 2 W.	Check steady-state, startup, and peak transmit supply demands.

$$E = P_{\text{in}} t = 2\,\text{W} \times 0.5\,\text{h} = 1\,\text{Wh}$$

Teaching assumption: Input power P_{in} stays at 2 W. E is energy (Wh), and t is time (h). The module consumes 1 Wh in 30 min, excluding power-conversion losses.

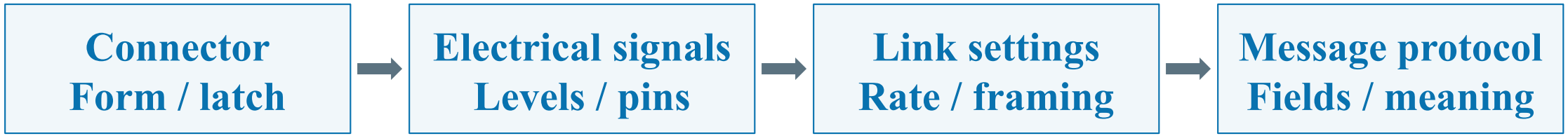
9.2.3 Hardware Characteristics and Interface Connections: Data Connectors

Connector Shape Does Not Guarantee a Data Rate

Form / series	Typical connection	What determines capability
GH, 1.25 mm pitch	Autopilot telemetry (TELEM), usually 6 pins; other counts exist.	Pinout, voltage levels, carried signals, and secure retention
USB Type-C	Onboard and ground computers. USB: Universal Serial Bus.	Port and cable USB/Thunderbolt version; power negotiation
RJ45 Registered Jack 45	Ethernet connections	Physical-layer transceiver (PHY), cable, and both endpoint rates; shape does not set speed.
Circular multipin connectors	MIL-DTL-38999 M12 and GX series	Series differ in locking, sealing, temperature, and weight. Check the model.

9.2.3 Hardware Characteristics and Interface Connections: Interface Checks and Connection Path

Match Mechanical, Electrical, and Protocol Requirements



Serial example: A universal asynchronous receiver/transmitter (UART) connects transmit (TX) to the other end's receive (RX). Check ground and logic levels.

Protection and installation: Blind mating, locking, vibration resistance, and waterproofing depend on the model and assembly, not appearance.

Mixed-signal example: The Mid-360 cable splits into power and Ethernet connections. Wire it according to the manufacturer's pinout.

9.2.3 Hardware Characteristics and Interface Connections: SMA, TNC, and MMCX

Antenna Connections Need Compatibility and Low Loss

Interface	Mechanical features	Check items
SMA / RP-SMA	SMA: SubMiniature Version A. Threaded coaxial. RP = reverse polarity, with changed center-contact pairing.	Plug/jack, center pin/socket, impedance, frequency, feeder loss
TNC	TNC: Threaded Neill-Concelman. Threaded coaxial coupling.	Vibration, fastening, rating. Used for reliable connections.
MMCX	MMCX: micro-miniature coaxial. Miniature snap-on coupling.	Space, mating, cable retention. Common in compact RF devices.

Textbook examples: SMA 18 GHz, TNC 11 GHz, MMCX 6 GHz.
Ratings vary by series. Connectors, feeders, and antennas must all support the operating frequency.

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9.2.4 Task-Based Hardware Selection Example

Textbook: Section 9.1.3 (integrated application)

9.2.4 Task-Based Hardware Selection Example: Payload Budget

Application Payload Sets the Initial Traffic Load

Assume 4 nodes, each generating 50 messages/s with 100 B of payload per message.
N is the node count, f the message frequency, and L the payload bytes per message.

$$R_{\text{payload}} = NfL \times 8 = 4 \times 50 \times 100 \times 8 = 160000\,\text{bit/s}$$

$$R_{\text{unicast}} = (N-1)R_{\text{payload}} = 3 \times 160 = 480\,\text{kbit/s}$$

R_{payload} sums all nodes' payload rates; R_{unicast} is the total rate for separate unicasts.
Broadcast 1 copy/message: 160 kbit/s; unicast to the other 3 nodes: 480 kbit/s.
Source load only: excludes headers, channel access, multihop forwarding, and retransmission.

9.2.4 Task-Based Hardware Selection Example: Protocol and Retransmission Overhead

Capacity Planning Includes Headers and Margin

Assume header $H = 40$ B, retry factor $\alpha = 1.2$, and planned utilization limit $u = 0.60$.
4 nodes, 50 messages/s each, 100 B/message. One initial copy/message; factor covers retries.

$$R = Nf(L + H) \times 8\alpha = 4 \times 50 \times 140 \times 8 \times 1.2 = 268.8\,\text{kbit/s}$$

$$C_{\min} = R/u = 268.8/0.60 = 448\,\text{kbit/s}$$

R includes headers and retries; $C_{\min}$ is the minimum capacity with utilization margin.
Load may use at most 60% of capacity. Compare capacities measured on the same basis as R.
A separate 345 kbit/s assumption falls below 448 kbit/s. It is not taken from Figure 9.2.

9.2.4 Task-Based Hardware Selection Example: Comparing Traffic Capacity

State and Video Need Separate Traffic Budgets

Traffic (assumed)	Four-node payload rate	Selection focus
State: 100 B at 50 Hz	0.16 Mbit/s, one source copy each	Timeliness, packet loss, and queues
Compressed video: 2 Mbit/s per node	8 Mbit/s	Uplink capacity, encoding, and buffering
State + video	8.16 Mbit/s, before protocol overhead	Isolate traffic; limit rates. Degrade under congestion.

$$R_{\text{raw}} = 1280 \times 720 \times 3 \times 8 \times 30 \approx 663.6\,\text{Mbit/s}$$

R_{raw} is the raw video rate of one node at 1280 × 720 pixels.
Uncompressed red, green, and blue (RGB): 3 channels, 8 bits each, at 30 frames/s.

9.2.4 Task-Based Hardware Selection Example: Discrete Updates and Results

Insufficient Capacity Creates Queueing Delay

Assume 400 B every 20 ms. At 120 kbit/s, the link sends 300 B per cycle.
Q is the queued byte count at cycle end, initially 0. Ignore headers and random access.

$$Q_{k+1} = \max(0, Q_k + 400 - 300), \quad Q_0 = 0$$

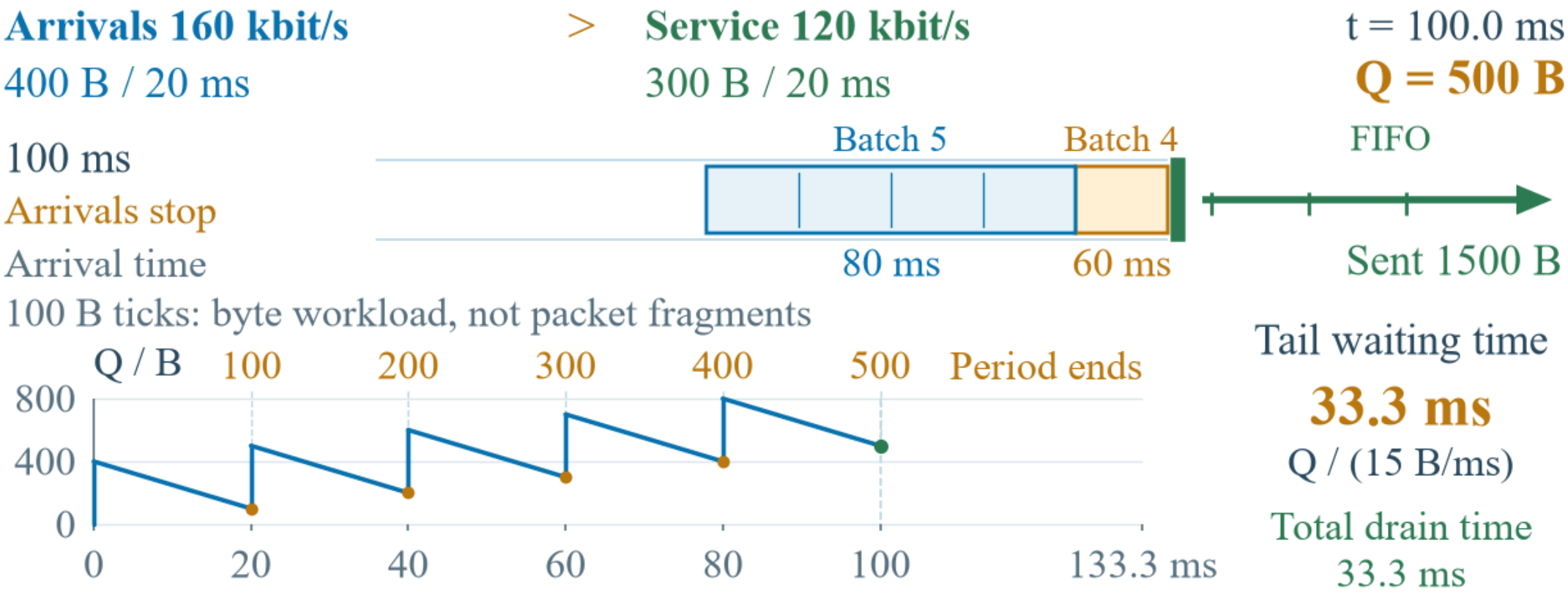
Cycle end k	1	2	3	4	5
Queued bytes Q	100	200	300	400	500

$$t_{\text{drain}} = 500 \times 8/120000 \approx 33.3\,\text{ms}$$

With arrivals stopped, t_{drain} clears the 500 B backlog in about 33.3 ms.
Continuing arrivals add 100 B/cycle until data is dropped or traffic is reduced.

9.2.4 Task-Based Hardware Selection Example: Queue Dynamics

Messages Accumulate When Generation Outpaces Transmission



First in, first out (FIFO): 400 B arrives every 20 ms, but the link can send only 300 B.

Exercises and Discussion

Selecting a Communication Configuration for Four Nodes

Question 1: Assume 4 nodes, 50 Hz, 100 B/message, a 40 B header, factor 1.2, and utilization limit 0.60.
Separately assume a 345 kbit/s link. Does it meet the capacity budget?

Question 2: If the update rate becomes 25 Hz, what is the minimum capacity? What is the cost in timeliness?

Question 3: A Type-C connector fits, but the device supports only a low-speed data mode. How would you diagnose and explain this?

Reference Answers

Capacity, Timeliness, and Interface Checks

Q.	Reference result	Limits of the conclusion
1	448 kbit/s > 345 kbit/s Insufficient for this plan.	345 kbit/s is an independent teaching assumption, not inferred from Figure 9.2.
2	224 kbit/s Generation interval: 20 ms to 40 ms	Capacity demand halves, but new state is generated less often.
3	Check port mode, cable, electrical configuration, and message format.	The Type-C form does not automatically guarantee 40 Gbit/s.

Section Summary

Task Metrics Guide Hardware Selection

Budget: Message size, frequency, and copy count determine load. Headers, retransmission, and forwarding consume capacity.

Mechanisms: Modulation, spreading, error correction, and retransmission affect efficiency and timeliness, subject to the actual channel.

Integration: Match size, power consumption, connectors, electrical signals, and protocols item by item.

Common errors: A frequency is not a technology name. MHz differs from Mbit/s. RF power differs from total power draw. Correct data can still arrive too late.